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**PHYSIOLOGICAL RESPONSES TO WBGT-EQUIVALENT
ENVIRONMENTS AND TWO CLOTHING TYPES DURING
SIMULATED DESERT MARCHES**

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**US ARMY RESEARCH INSTITUTE
OF
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We concluded that: (1) the modified BDU compounded the effects of the hot-wet environment; (2) different responses were observed in hot-wet vs hot-dry environments; (3) increasing the humidity from 48% to 80% (at 89°F) resulted in an elevated rectal temperature and a reduced plasma volume post-exercise; (4) significant hydromiosis occurred only during the hot-wet BDU trial; (5) sweat rate (but not sweat electrolyte losses), ventilation, and change in rectal temperature varied between trials, possibly explaining why symptoms of heat exhaustion and heat stroke vary between patients; and (6) equivalent physiological responses will not occur simply because hot-wet and hot-dry environments have equivalent WBGT values.

The following qualifications of these findings are recognized: (1) these results should be applied to acclimated/acclimatized soldiers only; (2) if full BDU had been worn, rectal temperature rise and sweat rate would probably have been exaggerated; (3) the impact of radiant energy from direct sunlight was not evaluated.



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TECHNICAL REPORT NO. T4/86

PHYSIOLOGICAL RESPONSES TO
WBGT-EQUIVALENT ENVIRONMENTS AND TWO CLOTHING TYPES
DURING SIMULATED DESERT MARCHES

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Table of Contents

	PAGE
List of Tables	IV
Abstract	V
Introduction	1
Methods	5
Results	8
Discussion	15
Responses to Environmental Treatments	15
Responses to Clothing Treatments	19
Hidromeiosis	21
Summary of Findings	23
Military Applications	25
References	28
Acknowledgments	32
Appendix A	33
Disclaimers	34

List of Tables

TABLE	LEGEND	PAGE
1	Mean (\pm SE) subject characteristics (n = 6).	9
2	Fluid and electrolyte parameters	11
3	Cardiorespiratory parameters	12
4	Body temperature parameters	13
5	Summary of Tables 2-4: statistical differences ($p < .05$) between comparable treatment groups.	14

Abstract

The purpose of this investigation was two-fold: (1) to determine if hot-wet and hot-dry environments were equally stressful to the exercising individual and (2) to examine the effects of clothing (shorts vs modified Battle Dress Uniform) worn while exercising in both environments. The physiological effects of exercise in a hot-humid environment (89°F, 80% RH) have been compared to those of exercise in a hot-dry environment (104°F, 28% RH), both equivalent to a WBGT temperature of 86.5°F. Six male soldiers walked on a treadmill in a climatic chamber, simulating a 3 hr desert march. Each soldier underwent five trials, on non-consecutive days: warm-dry in shorts, hot-wet in shorts, hot-wet in BDU, hot-dry in shorts, and hot-dry in BDU. Many significant differences ($p < .05$) in physiological responses were measured (Table 5).

We concluded that: (1) the modified BDU compounded the effects of the hot-wet environment; (2) different responses were observed in hot-wet vs hot-dry environments; (3) increasing the humidity from 48% to 80% (at 89°F) resulted in an elevated rectal temperature and a reduced plasma volume post-exercise; (4) significant hidromeiosis occurred only during the hot-wet BDU trial; (5) sweat rate (but not sweat electrolyte losses), ventilation, and change in rectal temperature varied between trials, possibly explaining why symptoms of heat exhaustion and heat stroke vary between patients; and (6) equivalent physiological responses will not

occur simply because hot-wet and hot-dry environments have equivalent WBGT values.

The following qualifications of these findings are recognized: (1) these results should be applied to acclimated/acclimatized soldiers only; (2) if full BDU had been worn, rectal temperature rise and sweat rate would probably have been exaggerated; (3) the impact of radiant energy from direct sunlight was not evaluated.

KEY WORDS: rectal temperature, heat illness, humidity, wet-bulb globe temperature, hidromeiosis, ventilation, water consumption, uniform, electrolytes, sweat, oxygen consumption, plasma volume

Introduction

In 1905, J.S. Haldane suggested that a wet bulb temperature reading described the intensity of heat stress more closely than a dry bulb reading (1). Since that time, at least ten major heat stress indices have been designed to equate environmental stress with physiological strain (2). The successful application of a single currently existing heat stress index to all military situations is impossible. The combinations of environmental conditions, morphology, clothing, metabolic work rate, inherent heat tolerance, physical conditioning, and heat acclimatization are almost endless. The most practical approach lies in using the heat stress index which is most suitable for the situation.

The U.S. Army has adopted the WBGT index as the best means of relating environmental stress to physiological strain in field situations. The validity of the WBGT index was ascertained by measurement of sweat rate, rectal temperature, and heart rate under conditions of desert heat (3). However, one must question the reliability of the WBGT index to predict heat stress in a hot, humid environment since cooling by evaporative heat loss is markedly reduced with increasing humidity. In addition to heart rate, rectal temperature and sweat rate, other physiological parameters (including blood pH, osmolality, glucose, CO₂ partial pressure, and bicarbonate; as well as ventilation, oxygen consumption, sweat electrolytes and skin temperature) have been basically ignored in the design and use of heat stress indices.

The dissipation of heat becomes increasingly difficult in conditions of high environmental humidity. While a hot-dry environment allows efficient sweat evaporation, a hot-wet environment reduces evaporative cooling and increases wasted, dripping sweat. The accumulation of sweat on the skin, due to either the high humidity or sweat-soaked clothing, results in increased skin wettedness and in a decline in sweat rate (known as hidromeiosis). Measurements of sweat rate during continuous exercise have revealed that sweat rate increases during the initial 60 min of exercise, but then decreases (hidromeiosis) for several hours (4). Gerking and Robinson (5) demonstrated that hidromeiosis persisted for up to 6 hr, during 50 min-10 min work-rest cycles, in both 90-100°F/humid and 104-122°F/dry environments. The most important implication of this work is that sweat rate might decline to such an extent that the production of sweat would be insufficient to meet the evaporative requirements of a working soldier, resulting in heat injury. Thus, the phenomenon of hidromeiosis confounds the interpretation of sweat loss data and may affect WBGT index interpretations to the extent that safe limits are not correctly estimated.

It is widely recognized that clothing also affects thermoregulation and sweating. Kamon (6) observed that clothing reduced heat exchange by as much as 40%. Similarly, Winsmann et al. (7) reported that four military uniforms reduced sweat evaporation by 15%, 18%, 21% and 29%, when compared to semi-nude trials. It is possible that a sweat-

soaked uniform produces a microenvironment above the skin which is equivalent to a very high ambient relative humidity, even under hot-dry conditions.

Up to 57 soldiers out of 1000 are afflicted with heat illness and are lost from duty each year. Heat exhaustion and heat stroke are characterized by elevated rectal temperatures and heart rates, tachycardia, and hypocapnia resulting from hyperventilation (8,9,10). The benefits of increased evaporative cooling gained by hyperventilation during hyperthermia may be overshadowed by the detrimental effects of the lowered blood carbon dioxide tension (P_{CO_2}), numbness, tetany and fainting observed in heatstroke (8,10,11). In spite of marked acid-base and ventilatory changes observed in heat injury only four studies have addressed the contribution of rectal temperature to ventilation in human subjects working in hot environments. These studies have supported other findings of an enhanced ventilation and lowered arterial P_{CO_2} during induced hyperthermia (0.6 - 1.0°C increase in rectal temperature) in resting human subjects (12,13,14,15,16,17). Petersen and Christensen (18) observed that acute hyperthermia during moderate exercise (rectal temperature $\geq 38.5^\circ\text{C}$) resulted in increased breathing frequency with no change in ventilation. In contrast, Ts'ao et al. (19) reported an enhanced ventilatory response to work in both hot-dry and hot-humid environments but only when rectal temperature exceeded 38.5°C in exercising subjects. Essentially, the role of hyperthermia in the control of ventilation during work in hot-dry or hot-wet environments is poorly defined.

Thus, this investigation was designed to answer the following militarily relevant questions:

1. What is the effect of a hot-dry vs a hot-wet environment at equivalent WBGTs on physiological measurements (sweat rate, sweat electrolyte losses, ventilation, heart rate, rectal temperature, and blood gases) during simulated desert and/or jungle marches?
2. What is the effect of clothing (shorts vs modified BDU) on these physiological measurements during simulated desert marches?
3. Is hidromeiosis observed when troops perform work in: (a) hot-dry vs hot-wet environments?
(b) shorts vs modified BDU?

This investigation compared two environments: hot-dry (104°F/40°C DB, 28% RH) and hot-wet (89°F/31.7°C DB, 80% RH). Even though the dry bulb and relative humidity readings differed widely, the WBGT readings were equivalent (both = 86.5°F/30.3°C WBGT). In addition, a mild environment (89°F, 48% RH) was tested, to provide comparative data at a lower WBGT (80.0°F). Wind velocity in all trials was 2.5 mph (1.1 m/s). This investigation also compared the physiological responses of men wearing nylon running shorts, socks and sneakers (SHORTS), to men wearing a modified Temperate Battle Dress Uniform (BDU). The modified BDU included t-shirt, BDU pants tied at the ankle, belt, socks, sneakers, and nylon shorts instead of underpants; no boots, hats, or BDU jackets were worn during these trials.

These environmental and clothing comparisons served to clarify the use of the WBGT index, to define the ventilatory and blood constituent responses to hot-wet and hot-dry heat stresses, and to allow recommendations regarding minimization of heat illness during exercise in the heat.

Methods

Three to five days prior to the initial day of testing (Day1), all subjects underwent a physical examination and recorded their food intake during two 24 hr periods. Food records were used to compare typical U.S. food constituents to the diets of our subjects. Bicycle maximal oxygen consumption ($\text{VO}_{2\text{max}}$) and maximal heart rate (HR_{max}) tests (4-5 continuous stages @ 60 rpm, see ref. 20) were conducted 3-5 days prior to Day1; height, weight, and estimated per cent body fat were also measured at that time.

Six healthy, heat acclimatized male soldiers underwent five 3 hr simulated desert walks in the NRDC Climatic Chambers during the month of August. All trials involved 45 min of treadmill walking (3.0 mph, 5% grade) and 15 min of rest each hour. Water was supplied ad libitum via canteens which were within reach of subjects while they walked and rested. Water consumption was measured to the nearest gram.

Upon arrival at the testing site each day (0700 h), subjects ate a breakfast of cold cereal, milk, juice, jelly and toast. The breakfast which was selected on Day1 was duplicated on each of the following test days (Day2 through Day5). Each

of the five trial days was identified by a letter (A through E); these labels head the columns in Tables 2-4. Trials were conducted in the following randomized order: A, C, D, E, B.

After eating, subjects voided bladder and bowel, took a pre-trial shower (no soap), had clothing (\pm 1g) and nude body weights (\pm 10g) taken, and then dressed. Skin thermisters, ECG leads, and a rectal probe were fitted at 0730 h. Skin thermisters were placed on the forearm, calf, and chest and a 3-point mean weighted skin temperature (MWST) was calculated. A venous catheter (QUIK-CATH, Travenol Laboratories, Deerfield, IL, 60015) was then placed in an antecubital vein by the attending Test Subject Medical Officer.

At 0800 h (REST1), subjects entered the climatic chamber, connected test leads, and participated in standing pre-trial measurements of heart rate (HR), and body weight (BW). Five minutes prior to collection, subjects breathed through a low resistance, small deadspace (175 ml) Collins valve. Expired gas was collected in a Douglas bag for approximately 2 min, and samples were taken for determination of oxygen (F_{O_2}) (Applied Electrochemistry SMA O_2 analyzer) and carbon dioxide (F_{CO_2}) (Beckman LB-2) content. The volume of the bag was measured with a Tissot gasometer (Collins). Expired minute ventilation (V_e) was measured and oxygen uptake (V_{O_2}) and carbon dioxide elimination (V_{CO_2}) were calculated. The pre-trial venous blood sample was drawn following a 20 min fluid equilibration period, during which the test subjects remained upright.

At 0830 h, subjects began exercise (WORK1). Skin temperature (T_{sk}) and rectal temperature (T_{re}) were recorded to the nearest 0.02°F every 4 min; HR was recorded every 5 min by ECG telemetry system. Subjects were removed from the trial if HR exceeded 180 beats/min, T_{re} exceeded 103.0°F , or if T_{re} rose 0.9°F or more during any 5 min period. The V_e and VO_2 measures were recorded during the last 10 min of each work period. Venous blood samples were analyzed for hematocrit (HCT) (microhematocrit), hemoglobin (HGB) (Hycel, Inc.), serum osmolality (Precision Instruments, Inc.), blood pH, blood gases including blood bicarbonate (Radiometer/Copenhagen ABL-2), blood glucose (Gilford), and blood lactic acid (LA) (Sigma). Plasma volume change ($\Delta\text{PV}\%$) was calculated using HCT and HGB (21).

After three work bouts of 45 min each (WORK1, WORK2, WORK3) and three rest periods of 15 min each (REST2, REST3, REST4), subjects left the climatic chamber at 1130 h. They removed skin thermisters, ECG leads, rectal probes, and had their clothing weight and body weight measured.

Sweat rate was calculated using clothing and body weight differences, taken before and after each work/rest period; corrections for water intake, urine output, and clothing absorption of sweat were applied. Sweat was collected using the whole-body wash down procedure developed by Vellar (22). The pre-trial shower removed electrolytes from the skin and hair of subjects. Subjects' BDU and SHORTS were cleaned each day to insure that no measurable electrolytes were in clothing

prior to WORK1. While in the climatic chamber, subjects blotted their bodies with electrolyte-free towels to collect dripping sweat; these towels were then placed in the eluent during the whole-body wash down. Clean polyethylene sheets were used to line the shower area and to retain the water which was poured over each subject's body (3.8-4.0 liters of deionized distilled water). Duplicate aliquots of the eluent were refrigerated for analysis of sweat electrolytes on a flame photometer (Radiometer/Copenhagen) and spectrophotometer (Gilford). The electrolyte loss (total mEq) was calculated by multiplying the volume of rinse water by the concentration of the electrolyte in the rinse water. Sweat electrolyte concentration (mEq/liter) was calculated using the total electrolyte loss (total mEq) and the sweat rate (total liters/hr).

Results

Selected descriptive characteristics of the six volunteers in this study appear in Table 1. Mean sodium intake--which affects water retention, sweat electrolytes, plasma volume and body weight--was within the normal range for 24 yr old U.S. males (23). The mean (\pm SE) spirometry values (n=6) for forced vital capacity (FVC) and forced expiratory volume in one sec (FEV_{1.0}) of 5.02 ± 0.25 liters and 4.13 ± 0.18 liters, respectively, were 91.2% and 97.5% of the predicted values. These findings, in concert with an FEV_{1.0}/FVC % of 82.8%, indicate that none of our subjects showed evidence of either restrictive or obstructive pulmonary disease.

Table 1 - Mean (\pm SE) subject characteristics (n = 6).

Age (yr)	Height (cm)	Weight (kg)	Body fat ¹ (%)	Bicycle HR _{max} (bpm)	Testing ² VO _{2max} (ml/kg/min)	Daily Dietary Intake		
						(Kcal)	sodium (mg)	(mEq)
24	175	76.19	18.7	191	45.0	2969	4873	212
± 1	± 3	± 5.50	± 1.6	± 3	± 1.7	± 343	± 1475	± 64

Notes: 1. skinfold caliper estimate

2. treadmill $\dot{V}_{O_{2max}}$ calculated at 49.5 ± 1.9 ml/kg/min, assuming bicycle $\dot{V}_{O_{2max}}$ is 10%

lower than treadmill $\dot{V}_{O_{2max}}$ test (9)

The treadmill work during these simulated desert marches (3.0 mph, 5% grade) caused subjects to work at an average of 44% of their treadmill $\text{VO}_{2\text{max}}$. Final mean steady-state LA concentration following WORK3 was 7.17 ± 0.32 mg%.

Tables 2, 3 and 4 describe values recorded during trials A through E. Values represent either the REST 4 (immediate post-exercise) vs REST 1 differences (+ symbol) or the measurement recorded at the end of WORK3 (* symbol). Statistical significance was tested using the appropriate t-test and significance was accepted at a confidence level of $p < .05$. Statistically significant differences ($p < .05$) between treatment groups are designated by brackets between the trials (Tables 2-4). Table 5 summarizes these significant between-group findings and offers an overview of differences in physiological responses between environments and between clothing types.

Surprisingly few differences ($p < .05$) were observed for fluid and electrolyte balance (Table 2) between the hot-wet and hot-dry environments. Whole body sweat rate, but not whole-body sweat electrolyte losses, exhibited several between-group differences. A significant within-trial decrease in sweat rate (hidromeiosis) occurred only when subjects wore the modified BDU during the hot-wet trial (Trial D; Table 2). Between-trial differences ($p < .05$) were observed in several cardiorespiratory parameters (Table 3) and body temperature (Table 4) parameters. The implications of these differences are discussed below.

Table 2 - Fluid and Electrolyte Parameters. Brackets indicate statistically significant differences between treatments ($p < .05$). Symbol + refers to REST4 - REST1 difference. Symbol ϕ indicates that measurements are not available. All values are mean \pm SE.

Measurement (unit)	Trial: Conditions: Clothing: n =	A 89°F, 48% RH shorts 6	B 89°F, 80% RH shorts 4	C 104°F, 28% RH shorts 5	D 89°F, 80% RH modified BDU 6	E 104°F, 28% RH modified BDU 6
Water intake (total ml/3 hr)		819 \pm 149	1472 \pm 1246	1523 \pm 355	1683 \pm 851	1128 \pm 625
Δ Body weight (%) +		-1.7 \pm .18	-1.0 \pm .5	-1.5 \pm .2	-0.4 \pm .3	-1.8 \pm .3
Sweat Na+ loss (total mEq/3 hr)		15 \pm 3	21 \pm 4	21 \pm 7	ϕ	16 \pm 6
Sweat K+ loss (total mEq/3 hr)		2 \pm 1	3 \pm 1	3 \pm 1	ϕ	2 \pm 1
Sweat Na++ loss (total mEq/3 hr)		ϕ	0.20 \pm .12	0.18 \pm .03	ϕ	0.26 \pm .10
Hidromeiosis during 3 hour trials ($p < .05$)		NO	NO	NO	YES	NO
Sweat rate (ml/3 hr) during WORK 1-3 and REST 2-4		3238 \pm 230	3923 \pm 561	4446 \pm 309	5549 \pm 711	5406 \pm 287

Table 3 - Cardiorespiratory Parameters. Brackets indicate statistically significant differences between treatments ($p < .05$). Symbol * indicates measurements taken at end of final work period. Symbol + refers to difference between WORK3 and REST1 values. All values are mean (\pm SE).

Measurement (unit)	Trial: Conditions: Clothing: n =	A 89°F, 48% RH shorts 6	B 89°F, 80% RH shorts 4	C 104°F, 28% RH shorts 5	D 89°F, 80% RH modified BDU 6	E 104°F, 28% RH modified BDU 6
Heart rate (beats/min) *		141 \pm 4	143 \pm 3.9	141 \pm 6.9	151 \pm 8.0	148 \pm 5.3
Δ Heart rate (beats/min) +		67 \pm 6	66 \pm 10	54 \pm 10	71 \pm 10	63 \pm 8
Blood pH (pH units) *		7.40 \pm .01	7.43 \pm .01	7.40 \pm .01	7.44 \pm .01	7.41 \pm .01
Ventilation (liter/kg/min, BTPS) *		.570 \pm .025	.547 \pm .037	.604 \pm .050	.691 \pm .043	.579 \pm .029
Oxygen consumption (ml/kg/min) *		21.41 \pm .56	20.90 \pm .87	22.36 \pm 1.14	23.37 \pm .93	20.57 \pm .50
Plasma osmolality (mOsm/kg) *		290 \pm 1	288 \pm 3	290 \pm 2	284 \pm 1	291 \pm 2
Δ Blood glucose (mg %) +		+3 \pm 4	-6 \pm 5	+7 \pm 5	-3 \pm 7	+6 \pm 6
Δ Plasma volume (%) +		+4.0 \pm 3.2	-3.9 \pm 1.6	+4.5 \pm 4.4	-0.9 \pm 1.8	+1.1 \pm 2.1
$P_{\bar{V}CO_2}$ (mm Hg) *		44.0 \pm 2.4	39.3 \pm 1.9	42.5 \pm 2.4	35.8 \pm 1.0	39.8 \pm 1.3
Blood $\left[HCO_3^- \right]$ (mEq/l) *		26.80 \pm .71	25.67 \pm .73	26.14 \pm .56	23.92 \pm .44	24.91 \pm .31

Table 4 - Body temperature Parameters. Brackets indicate statistically significant differences between treatments ($p < .05$). Symbol + refers to REST4 - REST1 difference. Symbol * indicates measurements taken at end of final work period. All values are mean \pm SE.

Measurement (unit)	Trial: Conditions: Clothing: n =	A 89°F, 48% RH shorts 6	B 89°F, 80% RH shorts 4	C 104°F, 28% RH shorts 5	D 89°F, 80% RH modified RDU 6	E 104°F, 28% RH modified RDU 6
Δ Rectal temperature (°F) +		1.55 \pm .14	2.54 \pm .32	0.74 \pm .22	3.15 \pm .31	2.11 \pm .29
Δ Mean weighted skin temperature (°F) +		-2.03 \pm .90	+1.15 \pm 1.79	+1.33 \pm .43	+2.75 \pm .76	+1.44 \pm 1.15
(Rectal temp.) - (MWST) (°F) *		10.31 \pm 1.12	6.71 \pm 1.26	5.04 \pm .70	5.31 \pm .38	5.26 \pm .99

Table 5 - Summary of Tables 2 - 4: statistical differences ($p < .05$) between comparable treatment groups. Comparisons between trials A and C, A and D, A and E, B and E, as well as C and D are not included because two coexisting variables were present.

Comparison of Trials	Environment	Clothing	Significant Differences ($p < .05$) Existed In:
1. A and B	89°F, 48% RH 89°F, 80% RH	shorts shorts	ΔT_{re} , $\Delta PV\%$, $(T_{re} - MWST)$
2. B and C	89°F, 80% RH 104°F, 28% RH	shorts shorts	ΔT_{re}
3. D and E	89°F, 80% RH 104°F, 28% RH	BDU BDU	$\left\{ \begin{array}{l} \dot{V}O_{2\text{submax}}, \Delta BW\%, P_{\dot{V}CO_2}, P_{\text{osm}}, \\ \Delta T_{re}, [HCO_3^-]_{p1\dot{V}}, \dot{V}_e \end{array} \right.$
4. B and D	89°F, 80% RH 89°F, 80% RH	shorts BDU	Sweat Rate, $\dot{V}O_{2\text{submax}}$, \dot{V}_e , $[HCO_3^-]_{p1\dot{V}}$
5. C and E	104°F, 28% RH 104°F, 28% RH	shorts BDU	Sweat Rate, ΔT_{re} , $[HCO_3^-]_{p1\dot{V}}$

Discussion

During extended desert/tropical field maneuvers, heat casualties may equal or exceed combat casualties if troops are not acclimatized, or do not follow proper water intake and work-rest cycle guidelines. For example, reports (24) indicate that during the 1967 conflict with Israel, the Egyptians suffered 20,000 heatstroke casualties during the Six Day War. These casualties accounted for approximately 50% of the total Egyptian deaths.

The measurement of the combined effects of heat and humidity is best accomplished by using the WBGT index (3,9) or the WGT (Botsball) index (25,26). The Botsball is a simple field instrument available through military supply channels (NSN 6665-01-103-8547) which reads WGT temperature in °F. However, the Botsball temperature may underestimate the WBGT temperature by 4-11 °C, under dry conditions (W. T. Matthew, unpublished observations, USARIEM, 1985) and may therefore be appropriate only in jungle environments. Only the WBGT temperature has been used throughout this report. This investigation clarifies physiological differences which can be expected when soldiers work in hot-dry environments (desert) vs hot-wet (tropical) environments, at equivalent WBGT (WBGT = 86.5°F for both: see Appendix A) temperatures.

RESPONSES TO ENVIRONMENTAL TREATMENTS

The Table 5 comparison of the mild trial A (WBGT = 80.0°F: see Appendix A) vs the hot-wet trial B (WBGT = 86.5°F: see

Appendix A) indicates that the elevation of humidity (from 48% to 80% RH) without alteration of environmental temperature, resulted in a significant difference in rectal temperature measured during the final work period. The rectal-to-skin temperature difference ($T_{re} - MWST$) was also significantly different, largely due to the reduced $\Delta MWST$ of trial A. Interestingly, subjective statements made by subjects supported these differences between the 48% and 80% relative humidities, indicating that subjects felt that the 80% RH environment was more oppressive than the 48% RH environment. Mean water intake during the humid trial (B), relative to the mild trial (A), was 45% greater but was not statistically different, due to the large variation observed during trial B (Table 2).

A comparison of trials B and C in SHORTS (both = 86.5°F WBGT) indicates that the hot-wet environment produced a markedly greater increase in rectal temperature than the hot-dry environment (Tables 4,5). Similarly, the hot-wet environment in BDU (trial D) caused a significantly higher rectal temperature than the WBGT-equivalent hot-dry conditions in BDU (trial E). These elevated rectal temperatures should have been accompanied by greater evaporation and cooling in the hot-dry environments, yet no significant differences in $\Delta MWST$ or sweat rate were noted between hot-dry and hot-wet environments. The explanation of these data may lie in alterations of tissue heat conductance, radiation, or convection (not measured).

Increases in both heart rate and rectal temperature have classically been presented as primary predictors of an increased heat load and dehydration during exercise in hot environments (27). Shvartz and Benor (28) reported that these two parameters were good indicators of tolerance time and heat strain during work in hot-dry conditions, but not hot-humid conditions induced by wearing vapor barrier suits. Kamon (6) demonstrated parallel increases in heart rate and rectal temperature, when relative humidity was raised at a constant ambient temperature of 36°C DB, but only after a "threshold" of approximately 65% RH had been reached. In the present investigation, no significant differences in heart rate or ventilation accompanied the increase in rectal temperature in soldiers wearing shorts, when relative humidity was increased from 28% to 48% to 80% (Trials C vs A vs B). Also, no difference in body weight loss, an index of dehydration, was observed between Trials C, A and B. The absence of changes in heart rate in the present investigation, whether they were or were not concurrent with changes in rectal temperature in hot-humid conditions, are at variance with the studies by Shvartz and Benor (28) and Kamon (6). These conflicting results may reflect the low relative humidity during Trial C (28% RH @ 40°C), in that a lower relative humidity will allow greater evaporative cooling.

The Table 5 comparison of trials D and E (both in BDU) indicates a variety of significant differences in a soldier's response to exercise in hot-wet vs hot-dry environments,

including: body weight change, plasma osmolality, plasma bicarbonate, venous CO₂, oxygen consumption, and ventilation. Differences in the first two of these parameters, body weight and plasma osmolality, indicate that test subjects had a larger body weight change and higher plasma osmolality under hot-dry conditions (trial E), without a significant difference in plasma volume. Noting the similarities in mean sweat rates, these body weight differences were probably due to the lower water intake in the hot-dry environment (Table 2). The latter four parameters present a unified picture (Table 3). The hot-wet environment (trial D) resulted in hyperventilation, decreased venous CO₂, decreased blood bicarbonate, a non-significant increase in blood pH, and a greater oxygen consumption.

Hyperventilation and concomittant hypocapnia have been used to characterize hyperthermic illness (8,10,11). Petersen and colleagues (17,29) have confirmed Dejour's finding of a rectal temperature threshold of about 38°C, or a change in rectal temperature of 0.6-1.5°C, above which hyperventilation is observed in resting or exercising man. A difference in rectal temperature of 1.04°C was observed between hot-wet BDU (Trial D) and hot-dry BDU (Trial E) trials, suggesting that rectal temperature (or core temperature combined with elevated skin temperature) exaggerated ventilation during the hot-wet BDU trial. However, differences in rectal temperature of 1.0 and 1.8°C were observed between Trials A and B, and Trials B and C, respectively, without significant increases in

ventilation. Therefore, factors not measured in this investigation may have contributed to the enhanced ventilation.

These facts bring an interesting point to light. Knochel's heat injury review article (8) notes that a long list of symptoms may be observed in cases of water depletion-heat exhaustion, including hyperthermia and hyperventilation. Yet such lists of symptoms are often derived by observing many case studies. It is widely recognized that not all symptoms of the different heat illnesses are observed in all victims (10,11). The results presented above indicate that it is possible that hot-wet environments produce physiological responses (i.e. hyperventilation) which are different from those in hot-dry environments (i.e. increased rectal temperature). Even though no actual heat exhaustion cases were observed during this investigation, our results may explain why heat exhaustion symptoms vary from one report to the next (8,10,11).

RESPONSES TO CLOTHING

A military uniform offers advantages and disadvantages to soldiers. In extreme heat, humans become almost totally dependent on evaporation of sweat for the cooling required to dissipate heat production, at rest and at work. A uniform, compared to a semi-nude garment such as SHORTS, reduces evaporation of sweat from the skin. Winsmann et al. (7) demonstrated that the BDU reduced evaporation by 29% (ambient conditions: 85°F, 70% RH), and "required substantially more sweat production per unit of evaporation" than other uniforms;

logically, this would apply to the BDU vs SHORTS comparison in the present study. In direct sunlight, however, a military uniform offers necessary screening from radiant energy (9) and should be worn by troops. This investigation clarifies physiological differences which can be expected when soldiers work in both hot-dry and hot-wet environments in BDU and SHORTS, but does not attempt to analyze the effect of radiant energy.

The Table 5 hot-wet (89°F, 80% RH) comparison of SHORTS (trial B) vs BDU (trial D) demonstrates that the oxygen consumption and ventilation were significantly higher in BDU clothed subjects. This may have been due, in part, to the added load (uniform weight, trial D) or alterations in the biomechanics of walking. Blood bicarbonate ($p < .05$) and venous PCO_2 (not significant) decreased in BDU. More likely, the higher ventilation observed in the BDU trial was due to higher rectal temperature (38.8°C) vs SHORTS (38.1°C). SHORTS resulted in a mean sweat rate which was 30% lower than that observed while wearing BDU, yet the mean changes in rectal temperature (2.54 vs 3.15°F) and $\Delta MWST$ (+1.15 vs +2.75°F) were statistically similar. In support of a previous study (7), we observed that BDU required considerably more sweat production per unit of evaporative cooling than did SHORTS.

The hot-dry comparison (104°F, 28% RH) of shorts (trial C) vs BDU (trial E) demonstrates trends similar to those seen during the hot-wet trial, for ventilation, oxygen consumption, venous pH, venous PCO_2 , and blood bicarbonate, although only

the latter parameter was significantly depressed ($p < .05$) during the BDU trial. Sweat rate was 18% lower ($p < .05$) in SHORTS; the Δ MWST and the rectal temperature-to-mean weighted skin temperature differential ($T_{re} - MWST$) were similar for trials C and E, yet the average change in rectal temperature (0.74 vs 2.11°F) was significantly higher in BDU. Thus, even though the BDU sweat rate was higher, this rate was unable to improve the evaporative cooling so that a rise in rectal temperature could be avoided. Evidently, this sweat was wasted or dripping sweat that was absorbed by the BDU and not evaporated for cooling purposes. This explanation is supported by the comparisons of trials B and C vs D and E above.

HIDROMEIOSIS

The mechanism of hidromeiosis is not well understood, but the following three hypotheses have been described:

- (a) sweat gland "fatigue" (5)
- (b) mechanical obstruction of the dermal pore (4)
- (c) an osmotic gradient between the sweat gland itself and the skin surface (30).

Although it is clear that hidromeiosis is most often associated with wet skin, it can be reversed by exposing a wetted skin to a dry environment, or by rapidly rehydrating the sweating individual (4). This latter point suggests a central mechanism, yet Candas et al. (31) have examined possible central controls without success.

During the present investigation, the only significant reduction in sweat rate (ANOVA analysis of WORK1 vs WORK2 vs WORK3) occurred within trial D (hot-wet, BDU). These hot-wet conditions produced a mean sweat rate decline of 48 % from hour 2 to hour 3 of trial D. This finding is in accord with many previous studies focusing on hidromeiosis (4), in that trial D allowed the least skin evaporative cooling due to the sweat-soaked BDU and the humid ambient conditions. Because the water deficit was not greater than 2-3 liters, one would not expect a decrease in sweat rate due to dehydration (32).

Hidromeiosis may be viewed as either beneficial or harmful, depending on one's viewpoint. Soldiers who experience hidromeiosis will have wet skin and will be living in humid conditions (or wearing wet clothing); it is likely that they will be sweating profusely and losing essential body fluids. Conversely, if sweat rate declines, a soldier will advantageously lose a smaller quantity of his total body water, but rectal temperature is more likely to rise. It is unlikely that this same soldier will store more heat if sweat rate declines during maneuvers, because hidromeiosis is reversed (sweating increases) if skin wettedness declines.

Hidromeiosis is only one of many physiological parameters undergoing change during exercise in the heat. To determine its impact on the soldier, each situation must be analyzed individually. However, it is clear that hidromeiosis is difficult to measure in the field because considerable expenditure of time and careful measurements are required.

Summary of Findings

The five simulated desert/jungle marches conducted during this investigation resulted in the following findings:

1. Hot-wet and hot-dry environments (of equivalent WBGT temperatures) produced different physiological responses. During the hot-wet trials, (a) rectal temperature was elevated (SHORTS and BDU), (b) oxygen consumption was higher (BDU), and (c) the ventilation, blood bicarbonate and venous CO₂ values indicated hyperventilation (BDU). During the hot-dry trials, loss of body weight was greater (BDU) primarily because less water was consumed and plasma osmolality was higher (BDU).
2. At 89°F, an increase of ambient vapor pressure from 48% to 80% RH (an elevation of WBGT from 80°F to 86.5°F) resulted in an elevated post-exercise T_{re} and a reduced plasma volume.
3. Wearing BDU (compared to SHORTS) resulted in:
(a) a much higher sweat rate (hot-wet and hot-dry),
(b) an increase in rectal temperature of 1.37°F (hot-dry), (c) increased oxygen consumption (hot-wet), and (d) hyperventilation, as indicated by increased ventilation (hot-wet) and decreased blood bicarbonate (hot-wet and hot-dry). The changes in ventilatory responses were possibly due to the increased rectal temperature and the load weight of the sweat-soaked BDU.

4. A significant within-trial decline in sweat rate (hidromeiosis) occurred only in the hot-wet BDU trial (Table 2).
5. No significant differences in water intake were observed between trials (Table 2), although water consumption in trial A (WBGT = 80°F) was noticeably lower than that of trials B, C, D and E (WBGT = 86.5°F). Based on previous investigations involving the human thirst mechanism (33,34), we speculate that the water intake would have been significantly lower if the WBGT of trial A had been lower, because the sensation of thirst would have been weaker.
6. Sweat rate (but not sweat electrolyte losses) varied greatly between treatments (Table 2).
7. In the trials which had a WBGT of 86.5°F (Table 4), Δ MWST did not differ. Rectal temperature was elevated in both BDU treatments (hot-wet and hot-dry) and in both hot-wet environments (BDU and SHORTS).
8. The differences in sweat rate, ventilation and change in rectal temperature, without significant differences in heart rate--observed during clothing and environmental treatments--may explain why symptoms of heat exhaustion and heat stroke vary between soldiers.

MILITARY APPLICATIONS

Several heat stress indices are available to predict the impact of environmental heat and humidity on a military unit (2). However, no heat stress index can be applied to every field situation. The WBGT index (3,9) is the most widely used of all heat stress indices. As the WBGT temperature rises above 82°F, U.S. Army guidelines recommend that water intake be increased and work-rest cycles be altered to include more rest each hour (see Appendix A). The use of the WBGT index has been clarified by this investigation. Medical Corps officers and commanders can expect soldiers to respond in different ways to WBGT-equivalent hot-wet and hot-dry environments. The most important of these differences are rectal temperature and fluid losses. At equivalent WBGT temperatures, heat injury casualties might even present different symptoms, depending on the combination of ambient dry bulb temperature and humidity.

The work by Yaglou and Minard (3) which first described the WBGT index, utilized sweat rate, rectal temperature and heart rate to evaluate the equivalency of different environments. Our data suggest that the inclusion of other parameters (e.g. oxygen consumption, ventilation, bicarbonate) in prediction equations might allow a more accurate heat stress index to be devised. This is especially true in light of the fact that exercise performed during this investigation was at about 45 % of $\dot{V}O_2$ max, the same exercise intensity observed during typical military duties in the field. Furthermore, the original WBGT work by Yaglou and Minard (3) strongly implied that an equal physiological strain resulted when humans were

exposed to WBGT-equivalent environments. The results of the present investigation clearly demonstrate that this is not true for rectal temperature, body weight loss, oxygen consumption, ventilation, plasma osmolality, and other parameters-- particularly when a uniform (BDU) rather than shorts were worn while working in hot conditions.

Heat acclimatization typically causes reductions in rectal temperature, sweat electrolyte losses, and heart rate, as well as increases in sweat rate and plasma volume. The soldiers who volunteered for this investigation were naturally acclimatized because trials were conducted during the month of August. These results, therefore, must be applied to unacclimatized troops with caution. These volunteers were also free from any known illnesses. If troops are not healthy, or if other predisposing factors to heat illness exist, these results might not apply. The list of factors which predispose an individual to heat illness is lengthy and includes: dehydration, diarrhea, fatigue, lack of sleep, fever, alcohol abuse, and poor fitness (9).

The clothing types tested in this investigation were SHORTS and BDU. The modified BDU was designed to match the clothing worn on a work detail in the heat. If full BDU had been worn during trials A - F, as was done in Winsmann's study (7), we speculate that physiological responses, such as rise in rectal temperature and sweat rate, would have been exaggerated.

No trials were conducted to evaluate the impact of radiant energy from direct sunlight. Wearing a hat and BDU jacket will

increase stored heat by reducing evaporative cooling and by trapping heat above the skin, but will also protect the skin from sunburn. Abnormalities of the skin and sweat glands (e.g. sunburn and heat rash) interfere with the ability to dissipate heat (9,10). The best approach in the field is to wear the least allowable amount of clothing. To maximize its effectiveness, clothing should fit loosely at the wrists, neck and lower legs to allow circulation of air (12).

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Appendix A

This appendix describes U.S. Army guidelines regarding water intake and work-rest cycles for heat acclimated military units during field operations. Note that the WBGT temperature is read from a WBGT meter, which combines dry-bulb temperature, wet bulb temperature and black globe temperature in one reading. Source: most recent revision to DA Circular 40-82-3 (26).

Heat <u>Condition</u>	WBGT Temp. <u>(°F)</u>	Water Intake <u>(qt/hr)</u>	Work-Rest Cycles <u>(min)</u>
-----	78-82	0.5	50-10
green	82-85	0.5-1.0	50-10
yellow	85-88	1.0-1.5	45-15
red	88-90	1.5-2.0	30-30
black	90 & above	2.0	20-40

Notes:

1. When the WBGT measurement falls exactly between two heat condition zones, apply the guidelines for the higher zone.
2. This work-rest cycle guideline depends on the status of troops.

Disclaimers

The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as official Department of the Army position, policy, or decision, unless so designated by other official documentation.

Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

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